Improving SWAT for simulating N$_2$O emissions from three cropping systems

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• Background
• Objectives
• Model development
• Model performance evaluation
• Sensitivity analysis
• Summary
Increasing evidences suggest that greenhouse gas (GHG) emission is a key driver of climate change.

Nitrous Oxide (N\textsubscript{2}O) is an important GHG due to its long lifetime and high global warming potential.
Green house gases (GHGs) balance of diverse cropping systems

Background

- Agricultural system is the primary N₂O emitter in the U.S.
Objectives

- Develop a N2O emission module for SWAT
- Evaluate model performance with site-scale observational data
- Improve parameterization of the module
- Analyze sensitivity of N2O estimates to key parameters and input driving forces
Model development

- Multiple numerical models have been developed to simulate N2O emission, including DAYCENT, DNDC, CLM, etc.

- Among these models, DAYCENT is the one that has been widely used and tested from site to global scales (Del Grosso et al, 2002, 2009)

- Current SWAT soil organic carbon processes were adopted from DAYCENT
Nitrogen Cycle

Atmospheric N fixation (lightning arc discharge)

Symbiotic fixation

Fertilizer

Manures, wastes and sludge

Ammonia volatilization

Runoff

Nitrogen Cycle

Denitrification

Anaerobic conditions

Leaching

Nitrification

Immobilization

Mineralization

Soil Organic Matter

N\(_2\)

N\(_2\)O

NO\(_x\)

NH\(_3\)

Fertilizer

Harvest
Model development \_ nitrification

\[ N_{\text{nit}} = f_{\text{moist}} \times f_{\text{st}} \times f_{\text{pH}} \times N_{\text{nit max}} + N_{\text{nit base}} \]

\[ f_{\text{moist}} = \frac{1}{1 + 30 \times e^{-9 \times \text{rel wc}}} \]

\[ f_{\text{st}} = e^{\frac{4.5 \times (1 - \frac{S - T}{40})^7 \times \left(-\frac{S - T}{40}\right)^{4.5}}{7}} \]

\[ f_{\text{pH}} = 0.56 + \frac{1}{\pi} \times \text{atan}(\pi \times 0.45 \times (SPH - 5)) \]

Soil water impacts

Soil T impacts

Soil pH impacts

\[ \text{NH}_4 \rightarrow \text{NO}_2^- \rightarrow \text{NO} \rightarrow \text{N}_2\text{O} \]
Model development\_denitrification

Denitrification

\[ \text{NO}_3^- \rightarrow \text{NO}_2^- \rightarrow \text{NO} \rightarrow \text{N}_2\text{O} \]

\[ E_{N2O\_den} = \frac{E_{den}}{1 + Rn2n2o} \]

\[ Rn2n2o = fRno3\_co2 \times fRfps \]

**Soil diffusivity impacts**

\[ fRno3\_co2 = 0.16 \times (38.4 - 350 \times dD0_{fc}) \]

**Soil water impacts**

\[ fRfps = 1.5 \times wfps - 0.32 \]

**Soil texture impacts**

\[ E_{Nden} = D_{totflux} \times fD_{fps} \times C_{unit} \times \rho_{soil} \]

**Soil CO₂ impacts**

\[ D_{totflux} = \min(fD_{co2}, fD_{no3}) \]

\[ fD_{co2} = 0.1 \times co2_{correction}^{1.3} - \min_{unit} \]
Model development: \( \text{N}_2\text{O} \) oxidation

\[
\begin{align*}
E_{\text{NO}_2\text{N}_2\text{O}} &= (E_{\text{N}_2\text{O}_{\text{den}}} + E_{\text{N}_2\text{O}_{\text{nit}}}) \times R_{\text{no}_2\text{N}_2\text{O}} \\
R_{\text{no}_2\text{N}_2\text{O}} &= 8 + \frac{18 \times \text{atan}(0.75 \times \pi \times (10 \times dD0))}{\pi}
\end{align*}
\]
Model performance evaluation site selection

A Corn site (M1), a switchgrass site (M3), and a reference site (M4) in the Marshall Farm Scale-up fields of GLBRC were selected for this study.

Figure 1. Locations of the three GLBRC scale-up experiment sites
• Soil water was sampled using the gravimetric method (original and dry weight difference)

• Sample were collected from the top 25 cm

• Simulated soil moisture was close to the average value of field data, or within one standard deviation of the average
- Default SWAT generally simulated well magnitude of N₂O fluxes

- Seasonal patterns of N₂O fluxes were reasonably simulated at M1 and M3, but not for the reference site (M4)

Figure 3. Model estimates of N₂O emission with default parameter values at the three sites.
Table 1 SWAT parameters controlling N$_2$O emission in nitrification and denitrification

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Default Values</th>
<th>Calibrated Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$adj_{fc}$</td>
<td>unitless</td>
<td>0.015</td>
<td>0.012-0.018</td>
</tr>
<tr>
<td>$adj_{wp}$</td>
<td>unitless</td>
<td>0.002</td>
<td>0.0019-0.0022</td>
</tr>
<tr>
<td>$wfps_adj$</td>
<td>day$^{-1}$</td>
<td>1</td>
<td>1.1-1.3</td>
</tr>
<tr>
<td>$\text{min_nit}$</td>
<td>unitless</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$f_{\text{nit_max}}$</td>
<td>unitless</td>
<td>0.15</td>
<td>0.13-0.17</td>
</tr>
</tbody>
</table>

Note: $adj_{fc}$ is the maximum fraction of N$_2$O to nitrified N at the field capacity; $adj_{wp}$ is the minimum fraction of N$_2$O to nitrified nitrogen at the wilting point; $\text{min\_nit} N_{\text{nit\_base}}$ is the minimum nitrate concentration required in a soil layer for trace gas calculation; $wfps\_adj$ is the adjustment on inflection point for water filled pore space effect on denitrification curve (unitless); $f_{\text{nit\_max}}$ is the maximum fraction of ammonia that is nitrified during nitrification (unitless).

we calibrated model parameters regulating N$_2$O production through nitrification and denitrification manually by adjusting parameter values to minimize the discrepancies between model estimates and field observation.
- The optimized parameter sets further reduced bias in estimated average N2O fluxes.

- Calibrated simulation also demonstrated better simulation of the seasonal patterns in N2O emission (P < 0.05).

Figure 4. Model estimates of N2O emission with calibrated parameter values at the three sites.
Comparison of default and calibrated simulations

<table>
<thead>
<tr>
<th>Simulations</th>
<th>$R^2$</th>
<th>Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M1</td>
<td>M3</td>
</tr>
<tr>
<td>Default</td>
<td>0.23</td>
<td>0.11</td>
</tr>
<tr>
<td>Calibrated</td>
<td>0.38</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Model performance evaluation

![Bar chart showing simulated N$_2$O flux (g N/ha/day) for models M1, M3, and M4. The chart includes observations and default and calibrated simulations.]
The new SWAT model explained up to 44.21% of the spatial variability in the multi-year average N₂O emission over three sites that represent a broad range of management activities.
Parameter sensitivity analysis

Table 2. Sensitivity response of N$_2$O emission to changes of key parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Changes in Parameter (%)</th>
<th>Changes in N$_2$O emission</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M1 site (%)</td>
<td>M3 site (%)</td>
</tr>
<tr>
<td>adj$_{fc}$</td>
<td>-20</td>
<td>-9.41</td>
</tr>
<tr>
<td></td>
<td>+20</td>
<td>+9.21</td>
</tr>
<tr>
<td>adj$_{wp}$</td>
<td>-20</td>
<td>-0.19</td>
</tr>
<tr>
<td></td>
<td>+20</td>
<td>+0.17</td>
</tr>
<tr>
<td>min$_{nit}$</td>
<td>-20</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>+20</td>
<td>-</td>
</tr>
<tr>
<td>wfps$_{adj}$</td>
<td>-20</td>
<td>+86.79</td>
</tr>
<tr>
<td></td>
<td>+20</td>
<td>-40.48</td>
</tr>
<tr>
<td>f$_{nit_max}$</td>
<td>-20</td>
<td>-3.62</td>
</tr>
<tr>
<td></td>
<td>+20</td>
<td>+2.35</td>
</tr>
</tbody>
</table>

Note: adj$_{fc}$ is the maximum fraction of N$_2$O to nitrified N at the field capacity; adj$_{wp}$ is the minimum fraction of N$_2$O to nitrified nitrogen at the wilting point; min$_{nit}$ N$_{nit\_base}$ is the minimum nitrate concentration required in a soil layer for trace gas calculation; wfps$_{adj}$ is the adjustment on inflection point for water filled pore space effect on denitrification curve (unitless); f$_{nit\_max}$ is the maximum fraction of ammonia that is nitrified during nitrification (unitless); ‘-’ indicate changes less than 0.01%.
Our sensitivity analysis suggested that N$_2$O emission had positive correlations with changes in precipitation at the selected sites; Warmer temperatures (2$^\circ$C increase) would further increase N$_2$O emission; Responses of N$_2$O emission to changing fertilizer use highlighted the significant control of chemical fertilizer application on N$_2$O production, particularly at the corn site (M1).

Table 3. Response of N$_2$O emission to changes in climate conditions and fertilizer use

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Changes in variable</th>
<th>Changes in N$_2$O emission</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>M1 site (%)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>-20%</td>
<td>-3.66</td>
</tr>
<tr>
<td></td>
<td>+20%</td>
<td>+1.39</td>
</tr>
<tr>
<td>Temperature</td>
<td>+1$^\circ$C</td>
<td>+3.69</td>
</tr>
<tr>
<td></td>
<td>+2$^\circ$C</td>
<td>+14.36</td>
</tr>
<tr>
<td>Fertilizer use</td>
<td>-20%</td>
<td>-16.25</td>
</tr>
<tr>
<td></td>
<td>+20%</td>
<td>+21.01</td>
</tr>
</tbody>
</table>

Note: Negative signs indicate decreases whereas positive signs suggest increases; ‘NA’ indicates not applicable.
Summary

- Developing N$_2$O emission module for SWAT is critical for strengthening the model’s capability in simulating agricultural ecosystems.

- New algorithms provide reasonable estimates of average N$_2$O fluxes over the three sites, but did not simulate seasonal patterns well at the M4 site.

- Parameter calibration substantially reduce bias in model estimates, and improve simulation of seasonal changes in N$_2$O fluxes over the three sites.

- Sensitivity analysis is expected to provide valuable information for future application of the model.

- Warmer and wetter climate scenarios tended to enhance N$_2$O emission over the study area.

- Sensitivity response of N$_2$O simulation to fertilizer use call for improved management practices to reduce fertilizer loss through N$_2$O emission.
Thanks